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RAINFALL STUDIES USING RAIN-GAGE NETWORKS AND RADAR

By H. E. Hudson, Jr., M. ASCE, G. E. Stout, and F. A. Huff

HYDRAULICS DIVISION

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PAPERS

RAINFALL STUDIES USING RAIN-GAGE NETWORKS AND RADAR

By H. E. Hudson, Jr.,[1] M. ASCE, G. E. Stout,[2] and F. A. Huff[3]

Synopsis

The results of three years' work on concentrated rain-gage networks and on measurements of rainfall extent and intensity by means of radar are described. Thunderstorm rainfall is shown to be multicellular, so that the application of area-depth data is more complex than is usually assumed.

The orientation, duration, and path of storm cells are shown to have marked effects on area-depth curves for a given basin. Data on area-depth relationships are presented for networks having areas of 5.2 sq miles, 95 sq miles, and 280 sq miles.

The effects of gage density on mean rainfall errors are investigated. The heaviest storms were found to be associated with cold fronts.

The theory and development of radar for rainfall measurement are reviewed. Available methods of measuring rainfall by radar are discussed. Data collected in the study on radar signal strength and rainfall intensity are presented and analyzed using a new analytical approach. It is concluded that radar is able to depict rainfall extent better than rain gaging, and that radar can measure rainfall intensities as ably as do the rain-gage networks generally used.

Introduction

The standard rain gage that has provided engineers with limited rainfall data may be replaced in the age of electronics. Radar, a high-frequency radio device, that became a reality during World War II, has since been used

Note.—Written comments are invited for publication; the last discussion should be submitted by September, 1953.

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by the Illinois Water Survey to detect, track, and measure quantitatively rainfall over the northern half of Illinois. The detection and tracking of rainfall were recognized by the military users of radar, but were not deeply explored by them for their application in the field of hydrometeorology.

Prior to the use of radar, rain-gaging techniques have not provided the accuracy desired by engineers and meteorologists. On the smaller watersheds under study in Illinois prior to 1948, gage densities of 15 sq miles per gage were used, but large differences of rainfall were encountered, especially when the precipitation occurred in the form of local showers or thunderstorms. In Illinois, the bulk of the year's precipitation comes from such storms.

When rainmaking was introduced in 1947, the Illinois Water Survey began to gather data on it. A corn company in El Paso, Ill., in cooperation with the Illinois Water Survey, organized a program to evaluate the possibilities of induced precipitation. A war surplus radar set was purchased by the cooperating group to be used for the tracking of both aircraft and rainfall during any rainmaking attempts. Gradually, although rainmaking did not seem

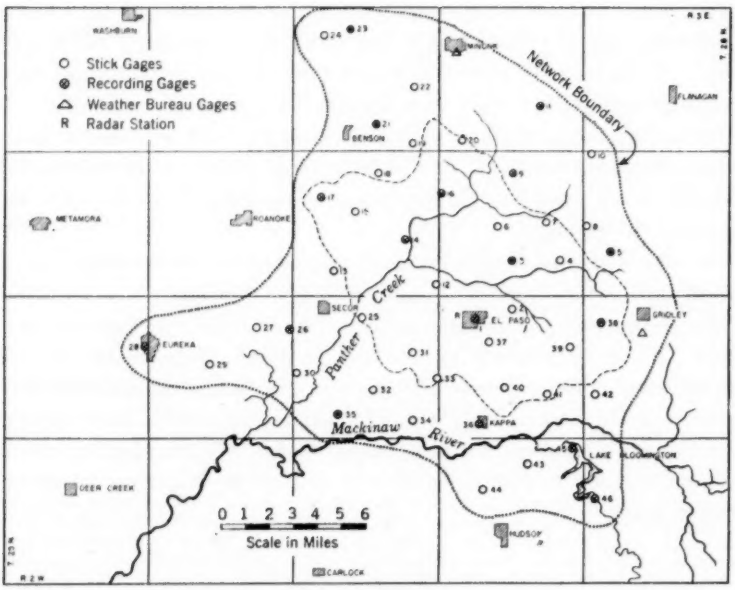

FIG. 1.—PANTHER CREEK RAIN-GAGE NETWORK (1948–1949)

to prove necessary in Illinois, the utility of the radar unit at El Paso for portraying the areal extent of the rainfall became evident. It was thought that, with this equipment, the quantity of rainfall could be determined, as well as the areal extent. Practically, it appeared that a radar scanning a radius of 70 miles or 15,000 sq miles could also determine the quantity of rainfall de-

posited in that area and thus supplement or even eliminate the standard rain gage.

As a check on the possibilities of the cloud-seeding work planned, a rain-gage network was installed in the vicinity of El Paso in the spring of 1948. This network, continued in revised form in 1949 and 1950, proved of little

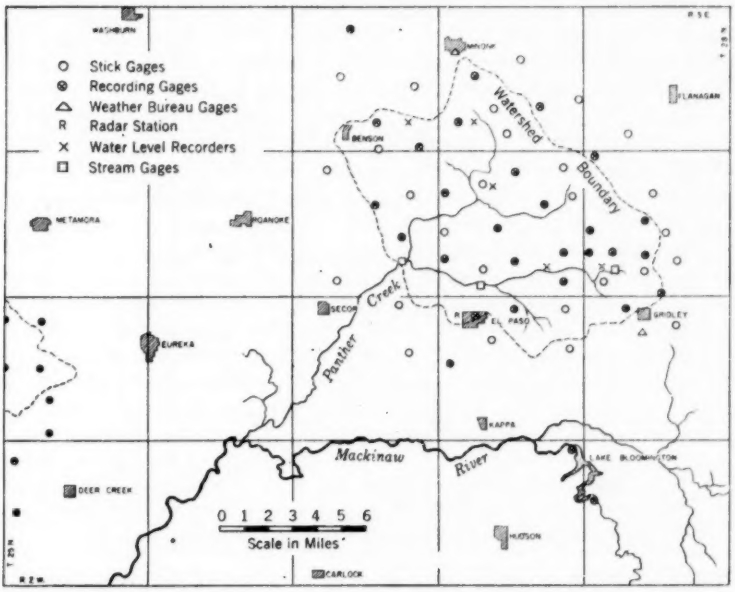

FIG. 2.—PANTHER CREEK RAIN-GAGE NETWORK (1950)

value for radar studies because of "ground clutter" appearing on the radar scope, caused by trees and structures close to the radar. However, the El Paso network did produce much thunderstorm rainfall data.

GAGE NETWORKS USED

Three rain-gage networks were available from 1948 through 1950 to make possible the analysis of the character of the storms involved in these studies. These networks are shown in Figs. 1, 2, and 3. The network covering 280 sq miles in the vicinity of El Paso (Fig. 1) was initiated in the spring of 1948. It was reorganized at the close of the 1949 thunderstorm season. Beginning in the spring of 1950, the Panther Creek network, as shown in Fig. 2, having an area of 95 sq miles, has been operated in conjunction with a detailed hydrologic study on that watershed located north of El Paso. The edge of the Farm Creek (a tributary of the Illinois River) network appears on the extreme left of Fig. 2. To obtain more rainfall data for this type of watershed, a different area of the same size and shape was chosen from the 280-sq-mile network in the area of maximum gage density. No distinct topographic or

climatic features exist in the region. The superimposed area is shown by the dashed outline in Fig. 1. The network of 5.2 sq miles, located on Boneyard Creek, at Champaign-Urbana, Ill., is shown in Fig. 3. This network has been operated since the fall of 1948 in cooperation with the Civil Engineering Department, University of Illinois, at Urbana.

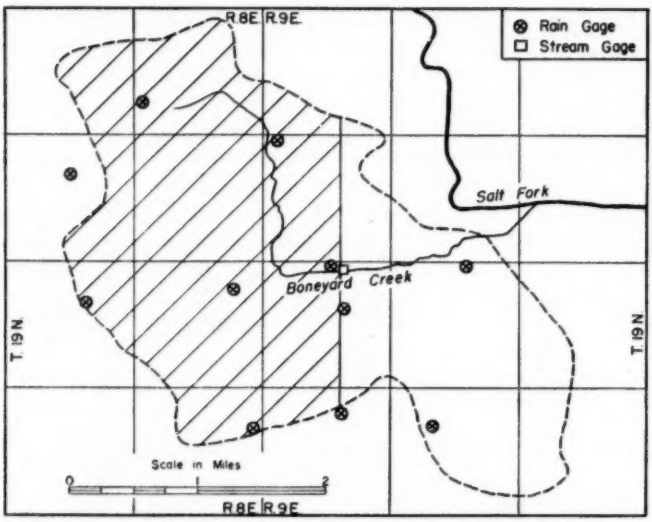

FIG. 3.—BONEYARD CREEK RAIN-GAGE NETWORK, URBANA-CHAMPAIGN, ILL.

The area of 280 sq miles, gaged in 1948–1949, contained a total of 29 stick gages and 17 recording gages, or an average of 1 gage per 6.1 sq miles. Within this area was the watershed of 95 sq miles that had 14 stick gages and 6 recording gages during the 1948 and 1949 seasons, corresponding to an average of 1 gage per 4.75 sq miles. During the 1950 thunderstorm season, 30 stick gages and 26 recording gages were located on, or in, the vicinity of the watershed of 95 sq miles. The Boneyard watershed included 7 recording gages, or an average of 1 gage per 0.7 sq mile.

AREA-DEPTH RELATIONSHIPS

For many engineering design purposes, a detailed knowledge of duration-area-depth relationships for small areas is essential. Few published data are available for areal units of less than 100 sq miles. Rain-gage networks of sufficient density to permit area-depth extrapolations (with reasonable accuracy) to such small areas seldom have existed. Rainfall data, collected on three networks of 5.2 sq miles, 95 sq miles, and 280 sq miles in central Illinois, have been analyzed in an attempt to furnish some concrete information on the characteristics of the area-depth curve for small watersheds in thunderstorm rainfall. The present analysis is concerned chiefly with the basin having an area of 95 sq miles, for which three years' data are available.

More limited data for the areas of 280 sq miles and 5.2 sq miles have been used to supplement this study. Only data for the thunderstorm season, between May and September, have been used in the analysis.

Effect of Gage Density on Area-Depth Curve.—During the summer of 1950, 40 gages were located in, or within, the boundaries of the 95-sq-mile Panther Creek watershed. For the 1948 and 1949 seasons, when a much larger area was gaged, only 20 gages could be included in an area having the size and shape of the Panther Creek watershed. Immediately, the question arose as to the comparability of the data; that is, what differences exist in the area-depth curve for an area of 95 sq miles when the results are based on a 40-gage network as against a 20-gage network?

Gage density in the following discourse refers to the average area per gage. The 40-gage network corresponds to 2.4 sq miles per gage and the 20-gage network corresponds to 4.75 sq miles per gage. To check the effect of gage density, the 8 storms of the 1950 thunderstorm season, having an areal mean rainfall in excess of 0.50 in., were analyzed using rain-gage networks of 40 gages and 20 gages on the watershed of 95 sq miles. Area-depth curves for each storm were determined by planimetering isohyetal maps. It was assumed that the 40-gage network yielded the true area-depth relationship. Interpolation was not extended to areas of less than 10 sq miles because it was felt that the 20-gage network was not dense enough for this purpose. (There is a tendency to underestimate the mean rainfall considerably for small units of area in which gage densities are insufficient to sample small intense cores of rainfall with accuracy.)

Percentage differences were determined by comparing the points representing areas of 10 sq miles, 25 sq miles, 50 sq miles, 75 sq miles, and 95 sq miles on area-depth curves for 20-gage networks and 40-gage networks. Although the 20-gage network did not provide isohyetal patterns of such fine detail, the variation in the constructed area-depth curves was less than 7% in each of the 8 storms studied. The mean variation was 1.2%. It was felt, therefore, that the 1948–1949 network of 20 gages per 95 sq miles (4.75 sq miles per gage) could be used for analysis with confidence in the results.

Because the 20-gage network seemed to give area-depth curves very close to the true curve, it was decided to investigate further the effect of gage density on the area-depth curve obtained. To do this, area-depth curves obtained from gage densities of 4.75 sq miles per gage, 9.5 sq miles per gage, and 19.5 sq miles per gage (20 gages, 10 gages, and 5 gages) for the 15 heaviest storms during the 1948–1950 period were compared. The results for densities of 9.5 sq miles per gage and 19.5 sq miles per gage were expressed as percentage differences from those obtained with the density of 4.75 sq miles per gage. The mean errors for the density of 9.5 sq miles per gage ranged from 3% to 6%; for the density of 19.5 sq miles per gage, they were from 4% to 7%. The results indicated, as would be expected, an increasing error with decreasing gage density, the error being greatest at the smaller units of area. Departures from the true mean were predominantly negative, demonstrating the tendency of the sparser networks to miss or underestimate the heavier cores of rainfall.

The 5-gage network was not extrapolated to areas of less than 25 sq miles because it correponds to only 1 gage per 19.5 sq miles.

Thunderstorm Rainfall.—H. R. Byers and R. R. Braham, Jr.,[4] have shown, as a result of radar-thunderstorm studies in Ohio and Florida, that the thunderstorm is normally of a multicellular nature. Usually a thunderstorm consists of three or more adjacent cells, each manifesting itself in the surface rainfall pattern. They found that single, isolated thunderstorm cells were comparatively rare and usually weak. The duration of moderate or heavy rain from a single cell of a storm was found to vary from a few minutes to almost an hour, depending upon the life of the cell.

The thunderstorm squalls preceding cold fronts, probably the most frequent source of heavy rainfall in the Panther Creek region and in much of the midwest, were found, in the writers' study, to be composed most frequently of several squall lines comprising a squall zone rather than a single line of thunderstorms. This discovery leads to the conclusion that the surface rainfall pattern is dependent on several factors—including the number, size, and longevity of the individual cells affecting the area, and their distribution of showers within the area of interest.

The thunderstorm project, described by Messrs. Byers and Braham,[4] found that these cells may vary from 1 mile to more than 30 miles in diameter. Consequently, these factors will be reflected in the area-depth curve. The complexity of the rainfall pattern will tend to increase with area and decrease with time; that is, the number of cores or centers of heavy rainfall associated with the individual cells will tend to increase with the area, especially with squall line conditions. The increasing number of cells crossing an area with progressing time will usally tend to make the total storm pattern more uniform because of the overlapping effect. For relatively large basins and short storm durations, the area-depth curve will often reflect a composite effect of several rainfall cores or centers within the area, rather than a pattern of high rainfall at one place decreasing progressively outward from the single center.

Some Factors Affecting Area-Depth Relationships on Individual Basins

The area-depth curve will be influenced by the size and shape of the basin, the orientation of the storm with respect to the basin, the topography, the duration of the storm, and the type of storm. The Panther Creek studies have been concentrated chiefly on the summer thunderstorm type of rainfall over this watershed, which is comprised of relatively flat terrain with no distinct topographic features. Therefore, for this investigation, three variables—the size and the shape of the basin, the general type of the storm, and the topography—are fixed. Efforts have been made to study the effects of storm duration and storm location with respect to the basin.

With respect to storm location, it may be stated that a given storm, consisting of a single rainfall core or storm center traveling along the minor axis of a rectangular basin, will produce an area-depth curve of greater slope than the

[4] "The Thunderstorm," Report of the Thunderstorm Project (A joint project of the U.S.A.F., U. S. Navy, National Advisory Committee for Aeronautics, U. S. Weather Bureau), Superintendent of Documents, Washington, D. C., June, 1949.

same storm having its center coinciding with the major axis of the basin; that is, the range of rainfall values from the lower end to the upper end of the curve will be greater. Similarly, when the storm axis passes near, or outside, the basin boundary, the slope will be greater than when the storm center passes through, or near, the basin center.

Area-Depth Analysis, Watershed of 95 Sq Miles, 1948–1950.—During the 1948–1950 period, 28 storms having mean rainfall in excess of 0.50 in. for the watershed of 95 sq miles were used in the study. Of these, 14 had the axis of the rainfall core passing near the center of the basin; the remaining 14 passed near the boundary of the basin. As would be expected, the heaviest areal rainfall occurred with those storms having their area of heaviest rainfall near the basin center. Because these are the storm types producing the heaviest rainfall for a given area, they have been analyzed separately. The results should be quite typical of area-depth relationships in heavy rainstorms.

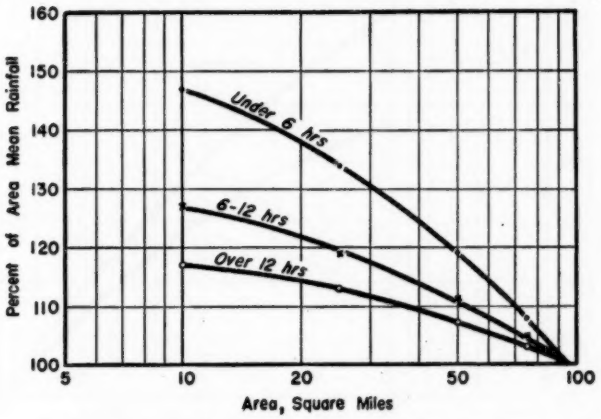

FIG. 4.—PERCENTAGE-AREA-DEPTH CURVES FOR 3 STORM DURATIONS (1948–1950) DATA

Percentage area-depth relationships for these 14 storms were listed in three classes, corresponding to rainfall durations of more than 12 hr (3 storms), 6 hr to 12 hr (5 storms), and less than 6 hr (6 storms). Fig. 4 shows mean-percentage area-depth curves for each of the duration classifications. Partial storm periods for several of the heavier storms have been used in the analysis because they comprised unit storms within the over-all storm period representing the passage of squall lines or zones. A further breakdown, involving the orientation of storm cores with respect to the basin axis, was not possible with the limited data. However, in these cases, it should be a minor factor because the basin is not of an elongated nature, being roughly equivalent to a rectangle of 9 units by 11 units.

Fig. 4 indicates that the slope of the area-depth curve tends to decrease considerably as the rainfall duration increases. This tendency is most pronounced when proceeding from the relatively short duration (from 1 hr to 5 hr) to moderate durations (from 6 hr to 12 hr). Variations between the percentage

area-depth curves for individual storms became smaller as the rainfall duration increased. For a specific duration, the variations between individual storms were less for large areas than for small areas. Considering the nature of thunderstorm rainfall, these indicated tendencies are quite logical. As mentioned previously, the thunderstorm is multicellular in nature, so that as storm duration increases and as the number of individual cells crossing a given area increases, there will be a greater tendency toward uniform areal rainfall.

Fig. 5 shows a comparison between 14 storms with storm axes located near the boundary of the 95-sq-mile watershed, with 6 storms having their core of heaviest rainfall near the central part of the basin. A comparison could be made only for storms having durations of less than 6 hr because all 14 boundary storms fell into this classification. As would be expected, the slope of the boundary storm curve is greater, as a rule. With respect to a basin, the rainfall

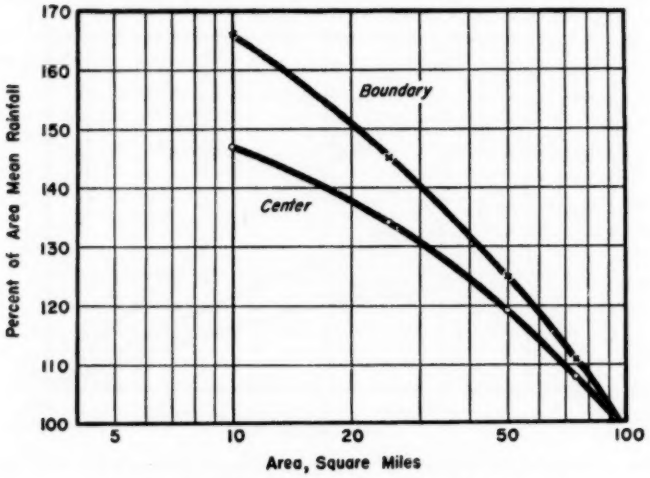

FIG. 5.—STORM CENTER LOCATION AND AREA-DEPTH DISTRIBUTION

gradient decreases mostly in one direction in the boundary storms. As a result, the mean rainfall for the total area decreases considerably compared to that of the same storm passing near the basin center. However, the maximum rainfall remains as great, or nearly so, as when the storm core is well within the watershed boundaries. This condition, of course, results in a greater slope for the area-depth curve in the case of boundary storms.

The limited data did not permit a thorough analysis of the possible effects of the magnitude of storm rainfall on the slope of the area-depth curve. The United States Weather Bureau study[5] of 38 6-hr partial storm periods found no evidence of any significant change in slope with increased mean rainfall in these 6-hr periods. The 14 storms examined in the writers' study point in the

[5] "Thunderstorm Rainfall," *Hydrometeorological Report No. 5*, U. S. Dept. of Commerce, U. S. Weather Bureau, and U. S. War Department, Corps of Engrs., Waterways Experiment Station, Vicksburg, Miss., 1947.

same direction. In comparing the 3 storms of greater than 12-hr duration, no significant differences in percentage values are evident, although mean rainfall varies from 2.57 in. to 5.22 in. Similarly, for the 5 storms of a duration of from 6 hr to 12 hr, there seems to be no significant correlation with mean rainfall, although amounts range from 1.14 in. to 2.77 in. A similar conclusion may be drawn from an examination of the storms of less than a duration of 6 hr. Rainfall duration appears to be more important than total thunderstorm rainfall in determining the slope of the area-depth curve.

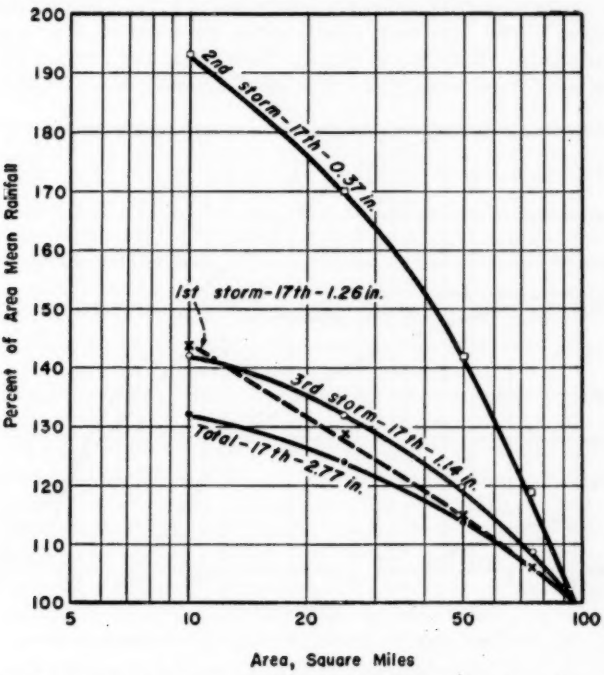

FIG. 6.—PERCENTAGE AREA-DEPTH COMPARISONS FOR PARTIAL STORM PERIODS AND FOR THE TOTAL STORM, JULY 17, 1950

The tendency for the area-depth curve to decrease in slope, with increasing duration of rainfall, is further illustrated in Fig. 6, in which percentage area-depth relationships for 3-hr intervals in the storm of July 17, 1950, are compared with the same values for the total 9-hr storm period. This storm consisted of two 3-hr periods of relatively heavy rainfall separated by a 3-hr period of relatively light precipitation. In connection with Fig. 6, it is interesting to note that the 3-hr period of light rainfall having the greatest slope showed the heaviest rainfall amounts near the edge of the watershed, but the axis of the rainfall core in the 2 heavy storms passed well within the watershed boundaries.

Comparison of Watersheds of 5.2 Sq Miles, 95 Sq Miles, and 280 Sq Miles.—A comparison of the area-depth data for the 95-sq-mile watershed was made

with those collected from the Boneyard watershed of 5.2 sq miles and the 280-sq-mile Panther Creek area. A comparison of the three areas was possible only for storms of a duration of less than 6 hr because insufficient data for the Boneyard watershed were available for longer durations. Fig. 7 shows this comparison for storms whose heaviest rainfall was located near the central part of the watersheds.

From Fig. 7, the tendency for storm rainfall variability to increase with increasing basin area is apparent. In referring to Fig. 7, it should be remembered that the average relationships for the watershed of 5.2 sq miles are not strictly representative of the maximum relationships for areas of 5 sq miles in the larger watersheds. With the increasing basin area, the number of thunderstorm cells, and, consequently, the number of intense cores of rainfall, tend to

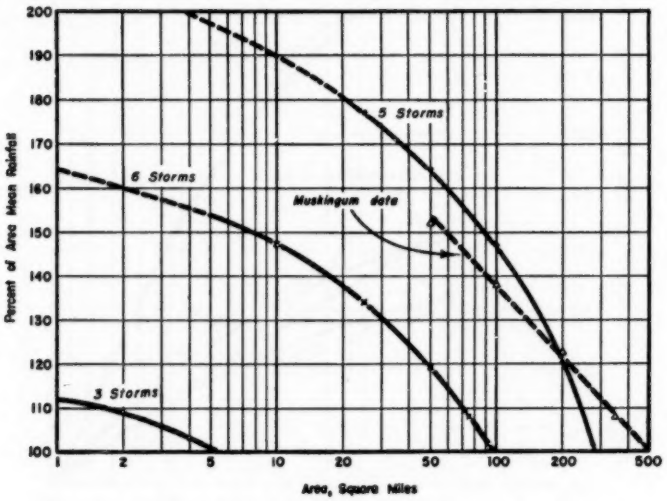

FIG. 7.—PERCENTAGE AREA-DEPTH CURVES FOR 3 NETWORKS IN ILLINOIS

increase. This condition results in a trend toward lesser variability in the area-depth curve within the very small areas of heaviest rainfall in the larger watersheds.

The dashed parts of the curves in Fig. 7 represent estimated relationships. Because the three curves for the individual watersheds are strikingly similar in shape, the curves for the basins of 5.2 sq miles and of 95 sq miles were used as guides in extrapolating the curve for the basin of 280 sq miles. This extrapolation was done by plotting the necessary parts of the two lower curves at the upper end of the curve for the area of 280 sq miles. Similarly, the curve for the area of 5.2 sq miles was used as a guide in extrapolating the 95-sq-mile curve. The results are presented as an approximation of the actual relationships, in the absence of more concrete data. As stated before, the direct application of the actual percentage values for a small watershed to the upper

end of a curve for a larger watershed would tend to produce erroneously high values. As an example, the ratio of the rainfall on 1 sq mile to the areal mean rainfall determined for the 95-sq-mile basin would be 1.71 by this method, but that obtained by the extrapolation method was 1.64.

The Muskingum data in Fig. 7 represent average values obtained from an analysis of 38 storms on the Muskingum Basin, in Ohio, by the Hydrometeorological Section of the U. S. Weather Bureau.[5]

Relations Between Gage Density and Mean Rainfall

It is important to know the reliability of mean rainfall values obtained from rain-gage networks of varying density which may be used for the determination of basin rainfall-runoff relationships. This fact is especially true for small watersheds with thunderstorm rainfall where only limited information is available, because rain-gage networks ordinarily employed do not provide sufficient data for such an investigation. Except for those provided by P. Light,[5] W. B. Langbein,[6] and Ray K. Linsley and Max A. Kohler,[7] very few data are available on the errors involved in the computation of areal mean rainfall.

Although the data collected from the concentrated networks used in this study are too limited to establish definite quantitative relationships, it is believed that they show the general magnitude of error associated with different gage densities for the size and type of watersheds investigated. The investigation is being continued to gather further information.

Data from the basin of 95 sq miles, described in the section on area-depth relationships (Figs. 1 and 2), were used in the study. Observations from 20 gages on this experimental area were available for the period between May and September, 1948–1949, and from 40 gages for the same period in 1950.

Analysis of Data.—It was assumed that the true mean rainfall was determined by the network of 20 gages on the 95-sq-mile watershed. This network corresponds to an average density of 4.75 sq miles per gage. Although, necessarily, the assumption involved some error, it was believed that it would be of small magnitude. As a partial check on the assumption, a comparison of results from 40-gage networks and 20-gage networks on the 95-sq-mile watershed for 1950 was made. This comparison revealed that maximum differences obtained from the two networks were less than 0.06 in.

Mean Error as Related to Gage Density.—The reliability of mean rainfall, as determined from networks of 10 gages, 5 gages, 3 gages, and 1 gage on the 95-sq-mile watershed, was investigated next. These networks correspond to average densitites of 9.5 sq miles per gage, 19.5 sq miles per gage, 32 sq miles per gage, and 95 sq miles per gage. Stations were chosen to give as uniform a network as possible in each case. In places where only one gage was used, it was the one most centrally located. Mean rainfall was classified into four intervals of from 0.01 in. to 0.20 in., from 0.21 in. to 0.50 in., from 0.51 in. to 1.00 in., and from 1.01 in. to 3.00 in., to determine the effect of storm magnitude

[6] "Error in Computation of Mean Areal Precipitation," by W. B. Langbein, U. S. Geological Survey, Superintendent of Documents, Washington, D. C., August, 1946.

[7] "Variations in Storm Rainfall over Small Areas," by Ray K. Linsley and Max A. Kohler, *Transactions*, Am. Geophysical Union, Vol. 32, No. 2, April, 1951, pp. 245–250.

on the error involved with each rain-gage network. The error in each case was determined from the difference between the 20-gage mean rainfall and that obtained from the network in question.

The results are shown in Fig. 8. It can be seen that, although the absolute magnitude of the error (in inches) increases with increased mean rainfall, it is proportionally smaller with the heavier storms. Based on an average for a number of storms, the mean error is relatively small, except for the heavier storms with the single gage. For general climatic purposes, therefore, it appears that concentrated networks, such as those employed in the 3-yr period studied, are not justifiable.

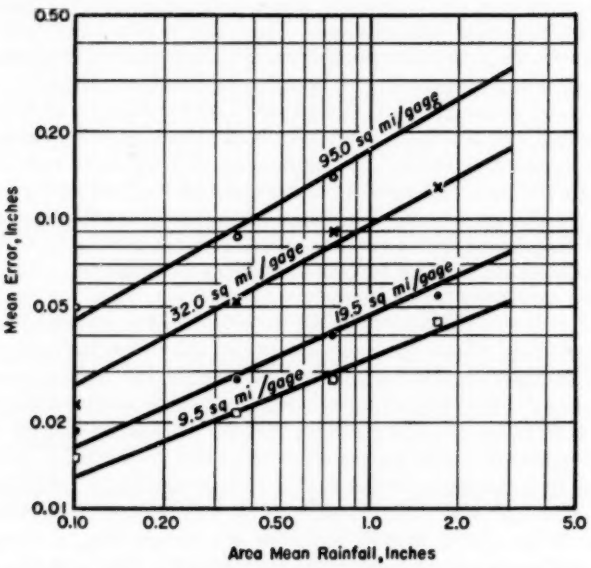

FIG. 8.—EFFECT OF GAGE DENSITY AND MEAN STORM RAINFALL ON MEAN ERROR, AREA OF 95 SQ MILES, 1948–1950

Error as Related to Gage Density, on a Monthly and Seasonal Basis.—Analysis was made of the errors for different gage densities by storms, on a monthly and seasonal basis. The data indicate that, for monthly rainfall, a network having 1 gage per 95 sq miles gave a mean error of less than 10% during two thirds of the months, especially during the months having the heavier areal rainfalls. Because the greatest errors would ordinarily occur during the thunderstorm season, it seems that a network of 1 gage per 100 sq miles should be sufficient for the determination of monthly or seasonal mean rainfall for most purposes. Monthly and seasonal accuracy improve only slightly with increasing gage density. The errors were predominantly negative, illustrating the tendency of the less dense networks to miss, or underestimate, areas of most intense rainfall. This fact, of course, is also true for storm rainfall.

Storm Type and Resultant Rainfall

Areal Mean Rainfall as Related to Storm Type.—The frequency distribution of areal mean rainfall by storm types over the 95-sq-mile basin for the thunderstorm seasons 1948–1950 was investigated. Storm precipitation was divided into five classes for this study. These classes included rainfall occurring with cold fronts, with pre-cold-frontal squall lines, with warm fronts or warm-air overrunning, with instability of warm-air masses, and with instability of cold-air masses.

The storm type associated with each rainfall occurrence was determined from the daily synoptic maps of the U. S. Weather Bureau. For the purpose of this investigation: (1) Cold-front precipitation was defined as that occurring from 100 miles in advance of the front until the ending of the rainfall with the frontal passage. (2) Pre-cold-frontal squall lines included those occurring in the warm-air mass from approximately 100 miles to 300 miles in advance of a cold front, and were considered to be indirectly associated with cold fronts. (3) The warm-front type of rainfall included that associated with the approach and passage of warm fronts or warm-air overrunning from stationary fronts located to the south. (4) Warm-air-mass instability rainfall was defined as that occurring in warm-air masses in the absence of fronts, and included thermal convection and nocturnal thundershowers. (5) Cold-air-mass instability showers included those occurring in the cold-air mass well after the passage of the cold front, usually associated with the passage of a trough aloft.

All storms resulting in an areal mean rainfall of 0.01 in., or more, were included in the analysis. In cases in which a warm-front passage was followed by a cold-front passage within a few hours, the rainfall associated with each system was determined from a study of the synoptic maps and the recording-gage records. A similar procedure was followed with fronts that became stationary over southern Illinois, after passing through the experimental area as cold fronts.

TABLE 1.—Areal Mean Rainfall as Related to Storm Type

Storm type	No. of storms	Percentage of total storms	Rainfall amount, in inches	% of total areal rainfall	Maximum individual storm, in inches
Cold front	49	38	18.66	40	2.02
Pre-cold-frontal squall line	16	12	12.42	26	2.77
Warm front	30	23	10.74	23	2.53
Instability of:					
Warm-air masses	30	23	5.28	11	0.76
Cold-air masses	5	4	0.12	0.3	0.05
Cold front plus squall line	65	50	21.08	66	

In Table 1, a comparison between storm type and areal mean rainfall has been summarized. As should be expected in the region in which the experimental area lies, precipitation was most frequently associated with cold fronts during the thunderstorm season. Similarly, the largest proportion of the areal mean rainfall was either directly, or indirectly, associated with cold

fronts. During the 3-yr period, cold fronts and pre-cold-frontal squall lines accounted for 50% of the total storms and 66% of the total rainfall.

Perhaps more significant to the hydrologist and meteorologist is the frequency distribution of the heavier areal mean rainfalls by storm type. Table 2 shows a comparison between storm type and areal mean rainfalls of 0.50 in.

TABLE 2.—AREAL MEAN RAINFALL AS RELATED TO STORM TYPE

Storm type	Minimum Depth of Rainfall, in Inches			
	0.50		1.00	
	No. of storms	Percentage of total storms	No. of storms	Percentage of total storms
Cold front	13	42	5	50
Pre-cold-frontal squall line	9	29	3	30
Warm front	5	16	2	20
Instability of:				
Warm-air masses	4	13	0	0
Cold-air masses	0	0	0	0
Cold front plus squall line	22	71	8	80

or more. It can be seen that cold-frontal squall lines and pre-cold-frontal squall lines were again dominant, accounting for 80% of the storm rainfalls of 1.00 in. or more and 71% of those equaling or exceeding 0.50 in. No warm-air-mass type (which includes heat-convection thunderstorms) gave an areal mean rainfall of 1.00 in. or more. Although the heat-convection thunderstorms may produce heavy rainfall intensities, they consist, normally, of scattered or isolated storm cells of small areal extent and short duration. Opportunities for heavy areal rainfall on a watershed of 95 sq miles are considerably greater with the multicellular-thunderstorm lines, or zones, associated with the approach and passage of cold fronts, in which rainfall may continue for several hours.

Rainfall Intensity as Related to Storm Type.—A study was made of the excessive rainfall rates recorded on the watershed of 95 sq miles between May and September, 1948–1950. Only data from recording gages could be used for this purpose. During the 1948 and 1949 seasons, 8 recording gages were included in the 20-gage basin network. The number of recording gages was increased to 24 during 1950.

Excessive rainfall rates were determined from the following U. S. Weather Bureau formula for short-period, high-intensity storms: $H = 0.01\ (t + 20)$, in which H is the rainfall, in inches, and t is the time, in minutes. Excessive rates were determined for 30-min, 1-hr, and 2-hr storm periods. Because weekly recording charts were used on the gages, the analysis of excessive rates for smaller units of time was not practical. Excessive rates for 30 min, 1 hr, and 2 hr correspond to 0.50 in., 0.80 in., and 1.40 in., respectively.

During the three thunderstorm seasons, there was a total of 25 storms in which excessive 30-min rates were recorded by one or more of the recording gages. Similarly, there were 19 storms in which excessive 1-hr rates occurred, and 9 storms with excessive 2-hr rates.

Storms associated either directly, or indirectly, with cold fronts were the chief sources of heavy intensities. Cold fronts and pre-cold-frontal squall lines accounted for 75% of the storms with excessive 30-min rates, 84% of those with excessive 1-hr rates, and 89% of the storms with excessive 2-hr rates. The maximum intensities recorded by an individual station occurred with a pre-cold-frontal squall line on July 16, 1950. A 30-min total of 1.46 in. was recorded by one station, whereas another recorded 1-hr and 2-hr totals of 2.25 in. and 2.72 in., respectively. This storm was also the source of the most widespread occurrence of excessive rates. For 30-min amounts exceeding 1.00 in., the cold-front systems were dominant, accounting for 7 out of 8 storms, with one or more stations recording over 1.00 in. in 30 min. Thus, storms associated either directly, or indirectly, with cold fronts were the most frequent source of rainfall, the source of the heaviest mean storm rainfalls, and the source of the heaviest rates of rainfall in the 95-sq-mile experimental area.

Radar Studies

The very close correspondence between the storm pattern shown by the radar and the rainfall pattern occurring on the ground has been established, but the possible application of this relationship in engineering meteorology has not been explored. Studies have been made by the Massachusetts Institute of Technology (MIT) Weather Radar Research Project, at Cambridge, whose report of December, 1946,[8] summarized the results previous to that date.

The United States Signal Corps has played a leading role in sponsoring the MIT work, and in carrying on a number of separate studies.[9,10,11] The British, through J. W. Ryde,[12] J. S. Marshall, and others of the Canadian Army Operational Research Group,[13] have contributed much to the theoretical knowledge of the relation of radar echo to rainfall and other meteorological parameters.

In the application of radar for storm detection, the Army-Navy-National Advisory Committee on Aeronautics-Weather Bureau Thunderstorm Project explored the structure and dynamics of the thunderstorm in great detail. In a preliminary study the possible use of radar in estimating the amount of rainfall over a small area[14] was established by Mr. Byers and others. The All-Weather Flying Division of the United States Air Force (USAF) recognized the possible uses of radar in aviation meteorology, and D. Atlas

[8] "M.I.T. Weather Radar Research, 1946," First Technical Report under Signal Corps Project, Dept. of Meteorology, Massachusetts Inst. of Technology, Cambridge, Mass., December 31, 1946.

[9] "Preliminary Report on Optimum Wave-length for Storm Detection," by D. Swingel and R. Wexler, *Technical Memorandum No. 183-R*, Evans Signal Labs., Belmar, N. J., November 7, 1945.

[10] "Rainfall Intensities and Attenuation of Centimeter Electromagnetic Waves," by J. Weinstein and R. Wexler, Evans Signal Labs., Belmar, N. J., 1947.

[11] "Ground Weather Test of AN/APQ-13A," by H. B. Brooks, *Technical Memorandum No. 193-R*, Evans Signal Labs., Belmar, N. J., April 17, 1946.

[12] "The Attenuation and Radar Echoes Produced at Centimeter Wave-lengths by Various Meteorological Phenomena," by J. W. Ryde, The Physical Soc. and the Royal Meterological Soc., Report of a conference held on April 8, 1946, pp. 169–189.

[13] "Measurement of Rainfall by Radar," by J. S. Marshall, R. C. Langille, W. McK. Palmer, *Journal of Meterology*, December, 1947, pp. 186–192.

[14] "The Use of Radar in Determining the Amount of Rain Falling Over a Small Area," by H. R. Byers, et al., *Transactions*, Am. Geophysical Union, Vol. 29, No. 2, April, 1948, pp. 187–196.

combined the theoretical and empirical weather radar equations to form the basis for a simplified radar-rain intensity computer.[15]

However, none of the foregoing projects has provided sufficient data and conclusions to establish radar as a dependable quantitative instrument.

Principle of Radar

The radar set emits a short, intense pulse of energy which may be focused into a narrow beam, and which travels at the speed of light. If the beam strikes an object, such as an airplane or a rainstorm, a small portion of the energy is reflected and returns as an "echo" to the point of transmission. It is then amplified and presented on a cathode-ray tube. The range and bearing of the object are determined readily. The beam usually travels along a "line-of-sight," hence, the radar cannot detect distant subjects that are near the earth's surface.

Theory.—Studies in this field indicate that the radar echoes from precipitation are the result of the scattering of radio energy by water drops falling through the atmosphere or suspended by strong vertical currents. The theoretical expression that has been developed[16] indicates that the energy (power) received from precipitation (reflected back to the radar antenna) is

$$P_r = C\,h\,P_t \frac{N\,a^6}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which P_r is the received power; C is a constant for the equipment used; h is the radar pulse width (duration, expressed as a distance); P_t represents the peak pulse transmitted power; N is the number of raindrops per unit volume; a^6 denotes the mean sixth power of the radii of the raindrops; and R equals the distance to the object. Eq. 1 may be expressed as $P_r = K_1 \frac{N\,a^6}{R^2}$, in which K_1 includes several of the constants.

From data collected by J. O. Laws and D. A. Parsons,[17] which indicate a relationship between raindrop size and intensity of rainfall, R. Wexler[18] has concluded that

$$\log N\,a^6 = 1.441 \log I - 17.302. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which I represents the rainfall intensity expressed in millimeters per hour; hence,

$$P_r = K_2 \frac{I^{1.441}}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Therefore, the problem in using radar for rainfall-intensity measurement seems to center around determining the power received (P_r) because that is a function of the intensity of the rainfall.

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[15] "Preliminary Report on New Techniques in Quantititive Radar Analysis," by D. Atlas, *Memorandum Report AWNW 7-4*, Pt. I, All-Weather Flying Div., AMC, U.S.A.F., October 22, 1947.

[16] "The Effect of Rain and Fog on the Propagation of Very Short Radio Waves," by J. A. Stratton, *Proceedings*, Inst. of Radio Engrs., June, 1930, pp. 1064–1074.

[17] "The Relation of Raindrop-Size to Intensity," by J. O. Laws and D. A. Parsons, *Transactions*, Am. Geophysical Union, Vol. 24, Pt. II, 1943, pp. 452–459.

[18] "Radar Detection of a Frontal Storm, June 18, 1946," by R. Wexler, *Journal of Meteorology*, February, 1947, pp. 38–44.

Radar Storm Presentation.—Fig. 9(*a*) represents a hypothetical storm 5 miles deep, of which the nearest edge is 15 miles east of the radar. The contours represent lines of equal rain intensity, the core of heavy rain being the innermost area. Numbers on the contour lines denote the rain intensity in inches per hour. When the radar antenna is directed along axis AB, Fig. 9(*b*)

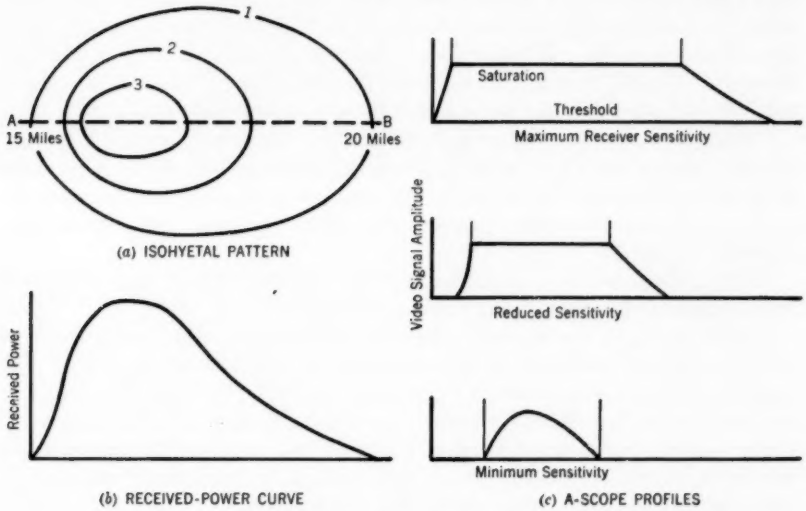


FIG. 9.—RECEIVED-POWER PROFILES (NO ATTENUATION)

represents the hypothetical received-power curve, corrected for range and attenuation. The "A-scope," a cathode-ray tube presentation used in many radar sets, portrays the observed data in a similar form. However, the receiver sensitivity is normally maintained at a high level so that light rain may be observed. As a result, the amplitude of the received-power curve exceeds the capacity of the receiver circuits, distorting the signal so that moderate rain intensities and cores of heavy rain cannot be distinguished.

The portion of the received-power curve observed by the radar operator on the A-scope is shown in Fig. 9(*c*). At maximum receiver sensitivity, only the base of the received-power wave form is presented. This base represents the area of light rain, but the heavier rainfall drives the circuits to saturation, thus flattening the top of the received-power curve. When the receiver sensitivity is reduced, greater received power is necessary to reach the threshold of visibility. It is necessary for the rain intensity to be greater for it to produce a detectable signal. Thus, the area of medium rainfall is presented. The receiver sensitivity may be reduced until only the received power from the core of heaviest rain is perceptible. The received power that will cause a barely-perceptible image on the scope is readily measurable.

A different type of presentation is obtained with the plan position indicator (PPI) scope. As the rotating antenna scans the entire area around the radar

set, the PPI presents an image of the storm as if it were laid out on polar coordinates. The area of rain glows, whereas the rest of the face of the scope is dark. Thus, the location and the areal extent of the storm are readily observed. Fig. 10(*a*) presents such a view, showing the scope and data of August 28, 1950, at 3:01 p.m., Central Daylight Time. Fig. 10(*a*) shows a heavy rain near Galesburg, Ill., 80 miles from the radar. For observing summer thunderstorm rainfall, the equipment used seemed to have an effective range of approximately 75 miles. To the right of the scope in Fig. 10(*a*) may be seen the date card, the 24-hr watch used to record the time of observation, the antenna-tilt indicator, and the light signals of the step-position indicator.

The outline of the image at different receiver-sensitivity levels should correspond to a rainfall-intensity contour. If the image on the PPI is recorded at several receiver-sensitivity levels, superimposing the areas enables construction of radar-rain-intensity contours that should coincide with actual rain-intensity contours.

Methods Available.—Two methods of varying the receiver sensitivity were used by the All-Weather Flying Division of the USAF.[18,19]

In one method, the receiver-sensitivity control was calibrated in terms of the echo power necessary for the threshold of visibility of the PPI. The operator changed the sensitivity manually, photographed the PPI image in each setting, and recorded the receiver-sensitivity setting for each picture. A picture taken at maximum sensitivity showed the outline of the entire storm and, at minimum sensitivity, the picture showed the locations of the cores of heavy rain (Figs. 10(*b*), 10(*c*), 10(*d*), 10(*e*), and 10(*f*)).

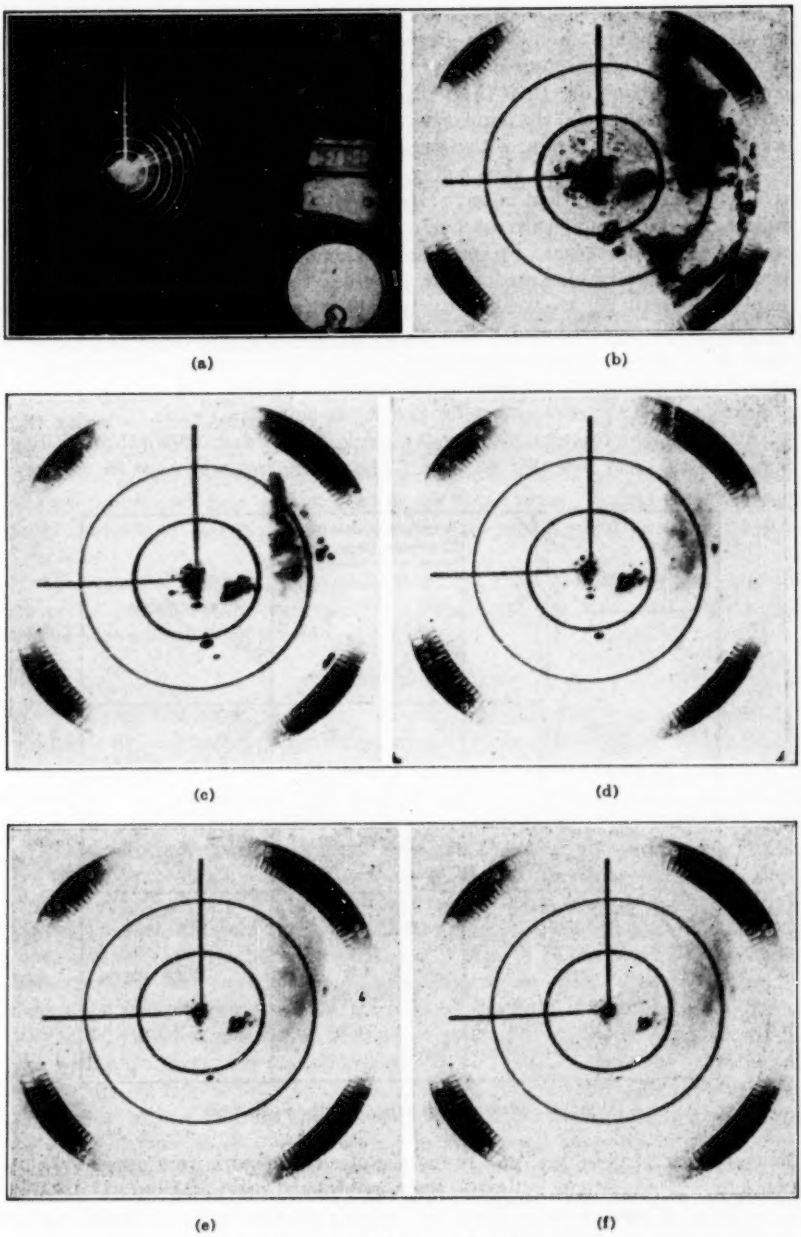
The second method used by the USAF all-weather group was the video-inversion method, which presents the storm structure as alternate bands of bright and dark areas. The light rain around the outside of the storm (the area between contours 1 and 2 in Fig. 9(*a*)) would appear bright, heavier rain (contours 2 to 3) would show as a dark area, and the core of the heaviest rain (inside contour 3) would appear as a bright area for the center of the storm. This method necessitates considerable additional circuitry.

Neither method seemed to fill all the immediate requirements. The video-inversion method requires a large number of additional tubes and associated circuits. Manual recording of sensitivity settings seemed laborious when several pictures were taken every minute. Because an automatic system of film recording was already in use, an automatic system of receiver-sensitivity control (synchronized with the camera) was developed.

Method

An AN/APS-15 3-cm radar set was used for the study. The radar set was located in El Paso. It was calibrated in nautical miles, and its peak power output averaged 25 kw. For this study, receiver sensitivity was varied by predetermined steps, and the storm pattern on the PPI scope was recorded on

[18] "Some Experimental Results of Quantitative Radar Analysis of Rain Storms," by D. Atlas, *Memorandum AWNW 7-4*, Pt. II, All-Weather Flying Div., Air Materiel Command, USAF, May 1, 1948.



(a) (b)

(c) (d)

(e) (f)

FIG. 10.—RAIN-INTENSITY CONTOURS

a 16-mm moving-picture film. An automatic photographic-recording and sensitivity-stepping circuit was devised. Known values of receiver power were put into the equipment to calibrate the circuit. A series of negatives exposed on August 30, 1950 (Fig. 10), shows the effect of step-wise receiver-sensitivity changes on the image on the PPI scope. The entire series was taken in a period of 1 min, with 10-sec intervals.

The first picture is on step 1 (Fig. 10(*b*)). The range-marking circles are at intervals of 10 nautical miles. Ground clutter, caused by reflections from buildings, extends out to almost 8 miles. The main area of the rain is the black portion to the northeast. A small area extends from 5 to 10 miles due east, and 4 showers are clustered about 10 miles to the south. In the second picture (Fig. 10(*c*)), the sensitivity is reduced to step 2. The areas of the rainfall images are reduced. The areas of light rain become imperceptible. Each successive step reduces the area of rain that is visible. On step 4, the core of only 1 of the 4 showers to the south is visible. On step 5, the core of heavy rain in the shower 8 miles east is the only rain visible.

All rainfall detected on the radar scope from June, 1950, through September, 1950, was recorded on film. The equipment was kept in readiness

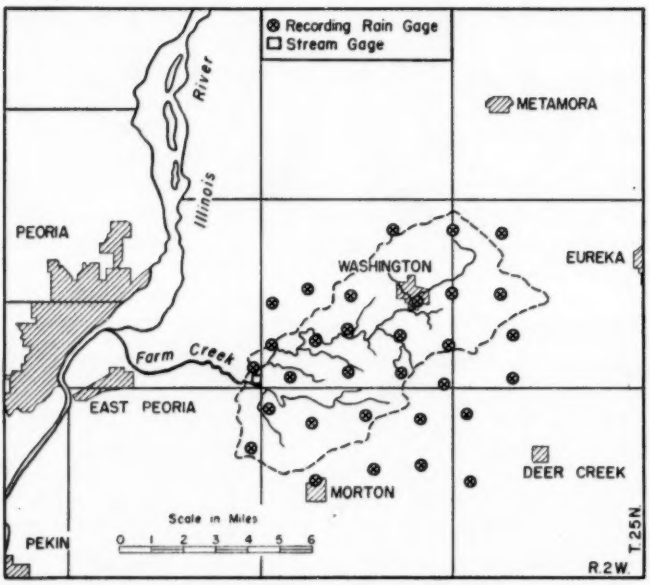


FIG. 11.—FARM CREEK RAIN-GAGE NETWORK, 1950

for operation 24 hr a day, and round-the-clock operators were present whenever synoptic conditions indicated the possibility of precipitation.

Rainfall Measurements.—To gather reliable rainfall data outside the zone of ground clutter, a network of weighing-bucket rain gages was placed in service

in July, 1950, in the vicinity of Washington, Ill. The network of 31 gages, 15 miles west of the radar station in El Paso, covers the watershed area of Farm Creek and some adjacent areas above East Peoria, Ill. The gages are generally spaced about 1½ miles apart (see Fig. 11). Collectors of 12.648-in. diameter were used instead of the standard units of 8-in. diameter. This use of larger diameter collectors expanded the sensitivity of the gages 2.5 times. The standard drum clock was geared for one drum revolution in a 6-hr period. Thus, 5-min rainfall amounts were easily determined, and 1-min rates-of-fall were computed with fair accuracy. A laboratory check is being conducted on the lag in the operation of the gages.

Rain fell during 18 days of the 74-day period of operation of the Farm Creek network. On 10 of these days, the average amount for the network was less than 0.10 in. On the remaining 8 days of rain, the daily totals were as follows: 0.12 in., 0.25 in., 0.31 in., 0.61 in., 0.75 in., 1.33 in., 1.47 in., and 2.54 in. Widespread shower activity, that produced rainfall between the network and the radar set, occurred on several days. This condition introduced an attenuation effect so that only 2 of the rainstorms could be used in the analysis described in this paper. On several occasions the radar set was not functioning properly, and data collected at those times were eliminated. The data from rainfalls of September 19, September 20, and September 21, 1950 were usable.

There were no cases of rainfall over the Farm Creek network that the radar did not detect and record. On a number of the light rains, only a part of the network received rainfall.

Analysis of Data

The data from the rain-gage network were compiled into a form readily available for any type of analysis required. Mean 5-min totals, the maximum rate during each 5-min period, and 1-min rates were tabulated and plotted for selected cases. Isohyetal maps were drawn for 5-min periods, and, frequently, for 1-min periods of precipitation over the network.

The radar data were transcribed from the 16-mm film to a base map 11 in. by 17 in., by projecting the photograph through a mirror system and a glass-topped copy table. The total area covered during each 1-min and 5-min period for each different receiver-sensitivity setting was drawn. These maps were termed "radar echo contour maps." Fig. 12 shows a 1-min radar echo contour map and the corresponding precipitation map. Discrepancies between the two patterns can be attributed to: (1) Failure of the radar to detect the entire depth of the storm because of attenuation; (2) time lag caused by the time of fall from the elevation at which the radar detects the raindrops to the earth; (3) lateral drift of the raindrops in falling; and (4) evaporation of the raindrops while falling. The areal extent of the precipitation, as observed by radar, correlates very well with the measured-rainfall pattern.

Mr. Atlas[19] found that there was a significant correlation between the intense rainfall cores, as observed in the lower 5,000 ft of the atmosphere, and those measured on the ground below. His best correlation resulted when the surface rainfall was measured at the core of the corresponding precipitation

pattern as the average rate over a 5-min interval immediately after the radar observation.

To compensate for the fall time and the drift of raindrops from the average height of between 2,000 ft and 3,000 ft, observed by the radar, successive 1-min maps of radar contours and of surface rainfall were used. The 1-min rainfall

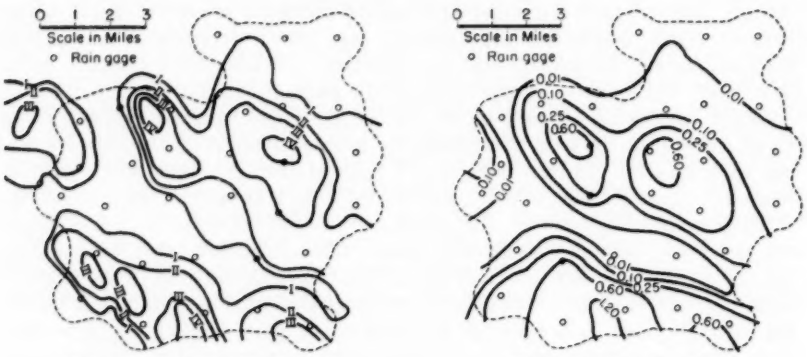


FIG. 12.—STORM PATTERNS DURING A 1-MIN PERIOD—BY RADAR AND BY RAIN-GAGE NETWORKS

rates were determined from the slope of the curve on the rain-gage chart. Using the sensitive rain gages, it was not difficult to observe rainfall depths as small as 0.005 in., with a time resolution of 1 min. Every change of slope, either large or small, was considered valid and used in the evaluation. In most cases, very minor irregularities did not have to be considered because fairly consistent rates persisted for at least 2 min or 3 min.

The direction and the amount of drift were determined from the movement of the radar cores for several consecutive minutes. The fall time of the raindrops was approximated by comparing a chosen 1-min radar profile along an appropriate radial from the radar station with consecutive 1-min surface rainfall profiles along the same radial line, after applying a drift correction to the surface rainfall pattern.

The successive 1-min rainfall profiles were compared with the radar profile until a matching of peaks for location was obtained (Fig. 13). The radar profile in Fig. 13 is along radial No. 5, between the hours of 0844.5 and 0845.5 on September 19, 1950. Only those cases in which the indicated time lag was less than 5 min, with the drift not greater than 1.5 miles, were used in the analysis. Cases involving intervening rain and core centers moving off the network were excluded. If the operators' log showed the possibility of instrumental error, or other observational inconsistencies, the data were discarded. Examples of very light shower activity were not considered. When more than one core of rainfall existed, it was often found that the time lag or the drift (or both) varied for each cell. Because the development stage of adjacent cells may vary considerably, this variation should be expected.

Fig. 14 summarizes the available data. For comparison with published measurements, a function of the received power was used for correlation. Values of $\frac{P_r R^2}{P_t}$ were plotted against the surface rainfall intensities, I_s, in inches per hour. A curve was fitted to the median values of the groups of values.

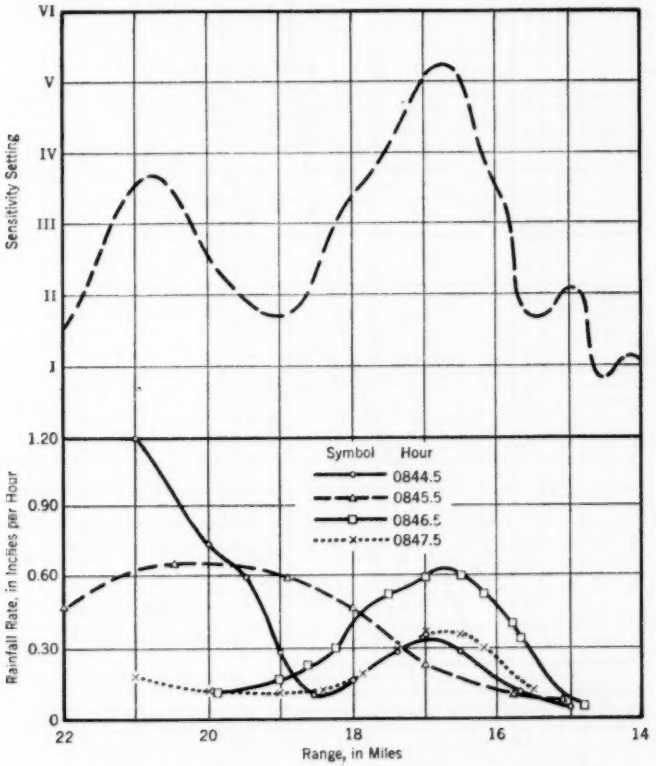


Fig. 13.—Profiles of Radar-Received Power and Rainfall Intensities

Conclusions

At rainfall rates below 0.7 in. per hr, there is reasonably good agreement between the observations gathered in this study and those made by Mr. Atlas. For higher rainfall rates, there are significant differences in returned-signal strength. The Illinois data failed to indicate the expected exponential relation between rainfall intensities and received power.

Previous studies have indicated that the received power from rainstorms should follow closely the Rayleigh scattering effect. The best available information on drop size[20] indicates that received power should be exponentially

[20] "Drop Size, Intensity, and Radar Echo of Rain," by A. F. Spilhaus, *Journal of Meterology*, August, 1948, pp. 161–164.

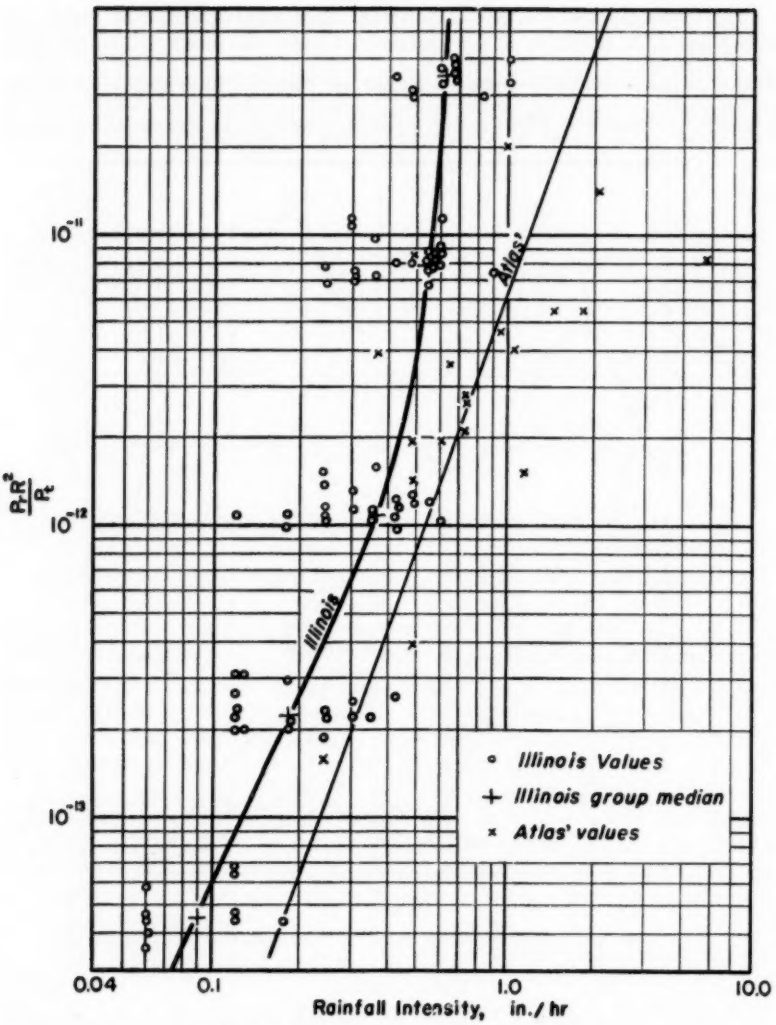


FIG. 14.—RECEIVED-POWER AND RAINFALL INTENSITY

related to rainfall intensity. These drop-size measurements were made at the ground surface, however, and the high received-power values at higher rainfall rates may indicate that large drops are present in higher concentrations at the elevations observed by the radar.

The scatter of actual measured-rainfall rates (by rain gages) shown in Fig. 14 was analyzed further to see whether the departures from the curve were such as to indicate any significant lack of correlation with signal strength and

range measurements. To do this, the mean rainfall departures from the values indicated by the curve were compared with the errors found associated with various rain-gage densities.

The dashed lines in Fig. 15 show the mean error (variation from the true mean) associated with the areal mean-storm-rainfall calculations when rain-

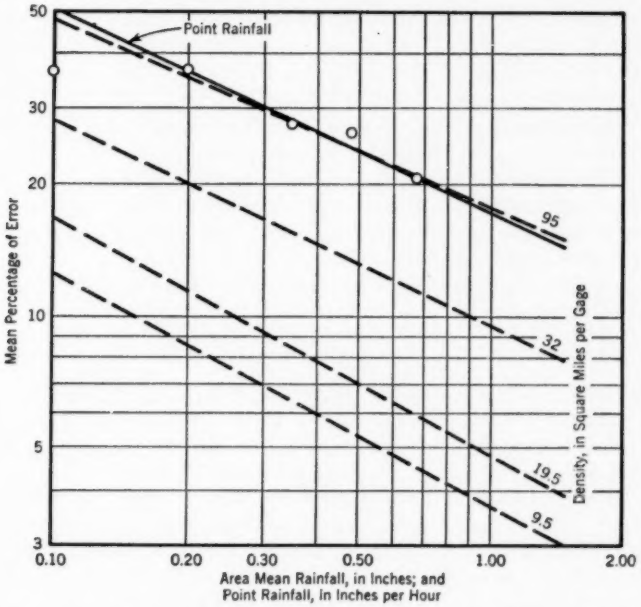


FIG. 15.—COMPARISON OF MEAN OBSERVATIONAL ERRORS—AREAL MEAN RAINFALL FROM RAIN-GAGE NETWORKS COMPARED WITH POINT RAINFALL INTENSITIES FROM RADAR OBSERVATIONS

gage networks of various density were used on a basin of 95 sq miles. The solid curve represents the mean variation associated with radar determinations of point rainfall intensities. The plotted points are mean values obtained from data for each of the five steps used in determining the "Illinois" curve of Fig. 14. These mean values were calculated from the following equation:

$$V = \frac{100}{N} \sum \frac{D}{I_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which V equals the mean variations; D equals the deviation of rain-gage rainfall intensity from the experimental curve value; I_g equals the rain-gage rainfall intensity in inches per hour; and N equals the number of observations.

Despite the limitations of the equipment used, the radar set appeared capable of determining point rainfall intensities as accurately as a rain gage network of 1 gage per 100 sq miles measured the mean areal rainfall.

Experience gained in this study indicated that the radar was equivalent to gage networks having approximately 1 gage per 3 sq miles for determining the

areal extent of rainfall. As further work is done, it is expected that increasingly close correlations between radar observations and rainfall intensities will be obtained.

Utility of Radar.—During the summer of 1950, regular rainfall reports, based on radar observations, were provided industry, agriculture, and the public through a local radio station. The U. S. Weather Bureau put the radar observations on its teletype to augment its information. In highway construction in central Illinois, it was found that the precise rainfall-location data often allowed the extension of operation beyond the usual periods of pouring concrete. Special short-range rainfall forecasts were made for the operations of a hybrid corn company, for the commencement exercises of a large university, and for the 1949 and 1950 Illinois state fairs.

Radar can depict precipitation patterns associated with flash floods, large floods, tornadoes, hurricanes, frontal weather, and freezing rain in winter. It should prove useful in irrigation works, and in controlling water-supply reservoirs and hydroelectric plants.

During succeeding years, radar will provide the answers to the area-depth questions asked by engineers.

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